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SEISMIC PHENOMENA CONNECTED WITH EARTHQUAKES AND EXPLOSIONS

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13. ABSTRACT

As stated in the semi-annual summary particular emphasis has been placed on the development of source theory and its incorporation into the calculation of synthetic seismograms in the frequency domain.

These techniques were used in the first half of the reporting period to determine theoretical M_S distance corrections; the effect of tectonic regions on the body wave spectra of explosions, and in the evaluation of long period discriminants.

This work is being continued and was used to determine the source parameters structure, and attenuation properties of the crust and upper mantle (e.g. Mitchell, 1973; Wiggins and Helmberger, 1973; York and Helmberger, 1973).

An improved monopole model of the earth's radial velocity and density variation was obtained by including differential travel times in the set of gross earth data used in the inversion algorithm (Jordan, 1973).

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I. <u>Summary</u>:

The research accomplishments during the past reporting period are given in the following abstracts. As stated in the semiannual summary particular emphasis has been placed on the development of source theory and its incorporation into the calculation of synthetit seismograms in the time and frequency domain.

These techniques were used in the first half of the reporting period to determine theoretical M_S distance corrections; the effect of tectonic regions on the body wave spectra of explosions, and in the evaluation of long period discriminants.

This work is being continued and was used to determine the source parameters structure, and attenuation properties of the crust and upper mantle (e.g. Mitchell, 1973; Wiggins and Helmberger, 1973; York and Helmberger, 1973).

An improved monopole model of the earth's radial velocity and density variation was obtained by including differential travel times in the set of gross earth data used in the inversion algorithm (Jordan, 1973).

1.

II. Abstracts of Publications and Reports During

this Contract Period

McKenzie, Dan, and Bruce Julian, "Puget Sound, Washington, Earth-
quake and the Mantle Structure Beneath the Northwestern United
States," Geol. Soc. America Bull., 82, 3519-3524, December 1971.

A detailed study of the travel time anomalies of the Seattle
earthquake supports the existence of a high-velocity slab dipping at
50^OE. beneath southwestern Canada and the northwestern United States.

Helmberger, Donald V., "Long-Period Body-Wave Propagation from 4° to
13°," Seismol. Soc. America Bull., 62, No. 1, 325-341, February 1972.

Numerical seismograms are computed for a compressional pulse
in a layered model. The simpler models consist of a fluid layer over
a fluid half-space, a fluid layer over a solid half-space, and a solid
layer over a solid half-space. Restricted portions of the theoretical
response for a layered model approximating the Earth are constructed.
Synthetic seismograms are generated using the pressure pulse appropri-
ate for NTS events and the long-period instrument response. The
interplay between the PL wave, the refracted wave along the lid, and
the arrival from the base of the low-velocity zone is displayed. A
detailed comparison between the synthetics and observations indicates
a prominent low-velocity zone with appreciable seismic absorption.
Observed regional wave-shape characteristics are displayed and a
reconnaissance map of lateral variations along the top of the mantle
presented.

Archambeau, Charles B., "The Theory of Stress Wave Radiation from
Explosions in Prestressed Media," Royal Astron. Soc. Geophys. Jour.,
29, 329-366, January 1972.

Stress wave radiation from underground explosions has been ob-
served to contain an anomalous shear wave contribution which is most
likely of tectonic origin. In this paper the theoretical radiation
field to be expected from an explosion in a prestressed medium is given
under the assumption that no secondary low symmetry faulting on a large
scale occurs and that the total tectonic component of the field is due
to stress relaxation around the roughly spherical fracture zone created
by the explosive shock wave. Evidence for the occurrence of this
simple kind of tectonic source is considered, and it is concluded that
this model is appropriate in many, if not most, instances involving
underground explosions. Expressions for the spectrum of the radiation
field and its spatial radiation pattern are given in terms of multipole
expansions for the components of the rotation potential and the

dilatation potential. Several possible rupture formation models are treated. All models show that the tectonic radiation is of simple quadrupole form, as has been observed. The energy radiated due to stress relaxation is considered in detail, and it is also shown that, in terms of the energy released, a dislocation source can be used as an equivalent for the stress relaxation effects.

The theoretical energy partition between compressional and shear waves for the tectonic field is in the ratio of (approximately) 1 to 10, so that tectonic stress release does not affect the direct compressional body wave particularly, but gives rise to totally anomalous SH polarized waves (e.g. Love waves) and affects Rayleigh type surface waves significantly, as is also observed. The theory can be applied to obtain estimates of source dimensions and the orientation and magnitude of the initial prestress field in the region of the explosion. In addition, application of this particular form of the general tectonic source theory to deep earthquakes and volcanic earthquakes also appears to be reasonable in view of the probable high symmetry of the failure or phase transition regions for such events.

Hanks, Thomas C., and Max Wyss, "The Use of Body-Wave Spectra in the Determination of Seismic-Source Parameters," Seismol. Soc. America Bull., 62, No. 2, 561-589, April 1972.

Teleseismic determinations of body-wave (P,S) spectra, interpreted in terms of the Brune (1970) seismic-source model, are used to estimate the parameters seismic moment (M_0) and source dimension (r) for three large, shallow, strike-slip earthquakes occurring on nearly vertical fault planes and for which the same parameters can be determined from field (F) data. These earthquakes are (1) the Borrego Mountain, California, earthquake (April 9, 1968) for which $[\bar{M}_0(P) = 10$, $\bar{M}_0(S) = 6.6$, and $M_0(F) = 3.6] \times 10^{25}$ dyne-cm and $[\bar{r}(P) = 14$, $\bar{r}(S) = 23$, and $L/2(F) = 17]$km; (2) the Mudurnu Valley, Turkey, earthquake (July 22, 1967) for which $[\bar{M}_0(P) = 9.1, \bar{M}_0(S) = 8.5$, and $M_0(F) = 7.4] \times 10^{26}$ dyne-cm, and $[\bar{r}(P) = 39, \bar{r}(S) = 48$, and $L/2(F) = 40]$km; and (3) the Dasht-e-Bayaz, Iran, earthquake (August 31, 1968) for which $[\bar{M}_0(P) = 4.8, \bar{M}_0(S) = 8.6$, and $M_0(F) = 18] \times 10^{26}$ dyne-cm, and $[\bar{r}(P) = 51, \bar{r}(S) = 48$, and $L/2(F) = 40]$km. The Brune (1970) model is well-calibrated with respect to the determination of these parameters for the earthquakes considered. A minimum estimate for the radiated energy can be expressed in terms of M_0 and r; this estimate is low by a factor of 10 with respect to the estimate obtained from energy-magnitude relations for these three earthquakes. The stress drops of these events are of the order of 10 bars.

Hanks, Thomas C., and Wayne Thatcher, "A Graphical Representation of Seismic Source Parameters," Jour. Geophys. Research, _77_, No. 23, 4393-4405, August 10, 1972.

The seismic source parameters seismic moment M_0, source dimension r, shear-stress drop $\Delta\sigma$, effective shear stress σ_{eff}, radiated energy E_s, and apparent stress $\eta\bar{\sigma}$ can all be expressed in terms of three spectral parameters that specify the far-field shear displacement of J. N. Brune's 1970 seismic source model: Ω_0 (the long-period spectral level), f_0 (the spectral corner frequency), and ε, which controls the high-frequency $(f > f_0)$ decay of spectral amplitudes. All the above source parameters can be easily extracted from a log-log plot of Ω_0 versus f_0 (ε when < 1 entering as a parameter), but only three of them are independent. The apparent stress is proportional to the effective shear stress, not the average shear stress. The Ω_0-f_0 diagram is especially convenient for comparisons within a chosen suite of seismic and/or explosive sources. The equation on which the Gutenberg-Richter energy-magnitude (E_{GR}-M_L) relation was originally based is cast into an approximate spectral form; E_{GR} can then be easily compared with E_s on the Ω_0-f_0 diagram for an earthquake of any M_L. Within the framework of the $(\Omega_0, f_0, \varepsilon)$ relations, it is a simple matter to construct an earthquake magnitude scale directly related to the radiated energy E_s.

Alewine, R. W., "Theoretical and Observed Distance Corrections for Rayleigh-Wave Magnitude," Seismol. Soc. America Bull, _62_, No. 6, 1611-1619, December 1972.

Examination of the distance correction factor used in the widely accepted formula for surface-wave magnitude reveals that this empirically derived linear formula fails to give an accurate approximation to the theoretical nonlinear amplitude-distance relation for epicentral distances less than 15^0. For epicentral distances greater than 15^0, the empirical formula contains an implied oceanic type energy-dissipation coefficient. When the original Gutenberg theoretical surface-wave magnitude formula with an appropriate continental energy-dissipation coefficient is applied to explosion data from the Nevada Test Site, a consistent surface-wave magnitude is obtained at all distances. A systematic method of normalizing Rayleigh-wave magnitudes obtained over different types of propagation paths is suggested. This normalization might provide a means for better separating natural events and explosions in the m_b-M_s plots.

Helmberger, D. V. and D. G. Harkrider, "Seismic Source Descriptions of Underground Explosions and a Depth Discriminate," Royal Astron. Soc. Geophys. Jour., 31, 45-66, August 1972.

Synthetic seismograms of both body waves and Rayleigh waves are used to determine the radiation field of a few large contained underground explosions. A number of possible source descriptions are investigated. A reduced displacement potential of the form, $\phi(t) = \phi_0 t^\xi \exp(-\eta t)$, fits the long- and short-period data. The source parameters appropriate for the Boxcar event are $\xi = 0.5$ and $\eta = 0.15$. Synthetic PL and Rayleigh waves are compared with observations from a number of different size events to determine the dependence of η on yield.

The amplitude of the long period synthetic body wave responses at ranges greater than about 12^0 increases rapidly as the source depth is increased. Thus the difference in spectral properties of explosions and earthquakes can be largely explained by the depth effect. The theoretical ratio SP/LP, that is the short period divided by the long-period amplitude, is computed from 12 to 25^0 for the Johnson upper mantle model and the Boxcar source. A study of an earthquake which cannot be distinguished from an explosion using the m_b vs. M_s criterion is investigated by the SP/LP discriminate.

Mizutani, H. and Katsuyuki Abe, "An Earth Model Consistent with Free Oscillation and Surface Wave Data," Phys. Earth Planet, Int., 5, 345-356, October 1972.

A suite of the most recently available geophysical data are inverted by a trial and error procedure with the help of the equation of state of some rock-forming minerals. An Earth model, designated as OC-1, is obtained to fit (1) the total mass and moment of inertia of the Earth, (2) free oscillation periods for fundamental spheroidal and torsional modes in the order number range n = 2-60, (3) phase velocity of Rayleigh and Love waves for pure-oceanic paths in the period range 100-325 s, and (4) group velocities of Rayleigh and Love waves for predominantly oceanic paths in the period range 100-325 s. This model has a well-developed low-velocity channel between 70 and 210 km, high density (3.50 g/cm^3) and high shear wave velocity (4.72 km/s) in the lid, and a negative gradient of shear wave velocity between 220 and 340 km. In the period range shorter than 250 s, the discrepancy between Rayleigh and Love waves may exist. The discrepancy may be resolved by introducing the small anisotropy of the partially molten low-velocity channel into the model.

Hill, David P., "Crustal and Upper Mantle Structure of the Columbia Plateau from Long Range Seismic-Refraction Measurements," Geol. Soc. America Bull, 83, 1639-1648, June 1972.

Seismic refraction measurements were made along a 600-km profile extending due south from the Canadian border across the Columbia Plateau into eastern Oregon. The source for the seismic waves was a series of 20 high-energy chemical explosions detonated by the Canadian government in Greenbush Lake, British Columbia. First arrivals recorded along this profile are on the Pn travel-time branch. In northern Washington and central Oregon, their travel time is described by $T = \Delta/8.0 + 7.7$ sec; but in the Columbia Plateau, the Pn arrivals are as much as 0.9 sec early with respect to this line. An interpretation of these Pn arrivals together with later crustal arrivals suggest that the crust under the Columbia Plateau is thinner by as much as 12 km or has an average P-wave velocity higher by as much as 0.8 km/sec than the 35-km-thick, 6.2-km/sec crust under the granitic-metamorphic terrain of northern Washington. A tentative interpretation of later arrivals recorded beyond 500 km from the shots suggests that a thin 8.4-km/sec horizon at a depth of 100 km may be present in the upper mantle beneath the Columbia Plateau and that this horizon may form the lid to a pronounced low-velocity zone extending to a depth of about 140 km.

Lambert, D. G., E. A. Flinn and C. B. Archambeau, "A Comparative Study of the Elastic Wave Radiation from Earthquakes and Underground Explosions," Royal Astron. Soc. Geophys. Jour. 29, 403-432, May 1972.

A detailed analysis of the surface wave radiation from two underground explosions (BILBY and SHOAL) and an earthquake near Fallon, Nevada, whose epicentre is only 60 km from SHOAL, indicates that: (1) at long periods the surface wave radiation from the earthquake can be explained by a pure quadrupole (double couple) source, but at higher frequencies the radiation pattern contains asymmetries which suggest effects due to rupture propagation; these would require higher-order multipole terms in the source equivalent representation; (2) the surface waves from the explosions can be explained by superimposed monopole and quadrupole sources, with no indication of higher-order multipole terms, at least in the period range comparable to that in which the earthquake signal was recorded; (3) the principal conclusion of this study is that the anomalous radiation from the explosions is probably due to stress relaxation around the shock-generated shatter zone and not due to earthquake triggering. Comparative analysis of SHOAL and FALLON shows that: (1) the ratio of the Love wave amplitude generated by the earthquake to the Love wave amplitude from the explosion increases with period, which implies a larger source dimension for FALLON; (2) the normalized spectral ratio of Love wave amplitude to Rayleigh wave amplitude, considered as a function of period, is nearly

constant and close to unity for the explosions, but larger for the earthquake by a factor of two or three, and increasing with period. These differences might be useful in distinguishing earthquakes from explosions (at least in the magnitude range of the events used in this study, m_b 4.4 and above), as well as for estimating source parameters, such as stress, which are of fundamental geophysical interest.

Mitchell, Brian J., "Radiation and Attenuation of Rayleigh Waves from the Southeastern Missouri Earthquake of October 21, 1965," Jour. Geophys. Research, 78, No. 5, 886-899, February 10, 1973.

The southeastern Missouri earthquake of October 21, 1965, generated fundamental mode and higher-mode surface waves that were widely recorded throughout North America. Amplitude radiation patterns for the fundamental and first higher Rayleigh modes were determined and compared with patterns computed for various fault plane solutions. The favored solution is that of a fault 4 km deep, oriented N70°E, dipping 50°S, and having a slip vector oriented 85° downward from the horizontal on the fault face. A least squares fitting process was devised to determine the source spectrum and the values for the Rayleigh wave attenuation coefficient at each period. The fundamental mode attenuation coefficient is slightly greater than 0.001 km⁻¹ at a period of 4 sec, decreases rapidly to 0.0002 km⁻¹ or less at periods between 17 and 25 sec, and increases slowly to about 0.00017 km⁻¹ at 50 sec. The first higher mode attenuation coefficients parallel and are slightly lower than those of the fundamental mode at periods between 4 and 10 sec. The source spectrum peaks between 5 and 9 sec and appears to attain a lower dc level at periods of greater than 20 sec. The similarity in the shapes and the orientations of the short-period radiation patterns and the area of perceptibility for this earthquake suggests that the size of the "felt area" of an earthquake is related to the nature of the radiation and the attenuation of short-period Rayleigh waves. This observation and the lower short-period Rayleigh wave attenuation coefficient values observed in the eastern United States in comparison with those observed in the western United States indicate that the larger areas of perceptibility of eastern United States earthquakes occur because short-period Rayleigh waves are transmitted more efficiently in that region.

Kurita, Tuneto, "A Procedure for Elucidating Fine Structure of the Crust and Upper Mantle from Seismological Data," Seismol. Soc. America Bull., 63, 189-209, February 1973.

A formulation is presented to elucidate the layered structure down to a depth of over 200 km from long-period body-wave records of teleseismic deep-focus earthquakes. This formulation utilizes the ratios

of vertical to horizontal motions of P and SV waves, and the ratio of SH motion to horizontal motion of SV waves. A strong advantage of the basic assumption of this method is that a postulation of horizontal parallel layering is limited to a few hundred kilometers. A two-step procedure is proposed and justified which makes a separate determination of the structure of crust and upper mantle. In each step, the truncated transfer ratio is used in which factors naturally incorporated in observed spectra, such as finiteness of the record, data window, instrumental response, source function, and later phases are all taken into account. Methods are developed to evaluate effects of the noise and the deviation of the direction of wave approach on the transfer ratio. This formulation makes it possible to elucidate the fine, regionalized structure of the crust and upper mantle such as transitional layering and details of the upper-mantle low-velocity zone.

A routine procedure for determining fine structure of the crust and upper mantle around recording stations is proposed. This cyclic procedure is a combined study of all available seismological methods such as body-wave transfer ratios, surface-wave dispersion, travel times, and synthetic seismograms, and a study of body-wave transfer ratios is in the heart of it. This approach leads to an unambiguous estimation of the layered structure in the upper part of the Earth.

Wiggins, Ralph A., and Donald V. Helmberger, "Upper Mantle Structure of the Western United States," Jour. Geophys. Research, 78, No. 11, 1870-1880, April 10, 1973.

Body wave observations from nuclear events at the Nevada Test Site and several earthquakes in the western United States have been used to construct models of the P wave structure for the upper mantle. The Cagniard-deHoop technique for computing synthetic seismograms for laterally homogeneous earth models was used to fit both the amplitudes and the travel times of the observations. Below a depth of 300 km one model fits all the observations remarkably well. This model has sharp discontinuities at 430 and 650 km and a discontinuity in slope at about 550 km. Above 350 km the observations can be divided into two groups according to the location of the point of deepest penetration of the rays. The difference between the areas is due primarily to the size of the low-velocity zone and the magnitude of the velocity immediately below the low-velocity zone.

York, James E., and Donald V. Helmberger, "Low-Velocity Zone Variations in the Southwestern United States," Jour. Geophys. Research, 78, No. 11, 1883-1886, April 10, 1973.

Time differences between arrivals of P and PL waves on 55 seismograms from 13 events were measured and compared with model study

values. Variations are mapped as a point midway between station and event for each measurement. The results are presented as a contour map of large-scale lateral variations in the upper mantle beneath the western United States.

Whitcomb, J. H., "Part I. A study of the velocity structure of the earth by the use of core phases. Part II. The 1971 San Fernando earthquake series focal mechanisms and tectonics," Ph.D. Thesis, California Institute of Technology, 1973.

The initial objective of Part I was to determine the nature of upper mantle discontinuities, the average velocities through the mantle, and differences between mantle structure under continents and oceans by the use of P'dP', the seismic core phase P'P' (PKPPKP) that reflects at depth d in the mantle. In order to accomplish this, it was found necessary to also investigate core phases themselves and their inferences on core structure. P'dP' at both single stations and at the LASA array in Montana indicates that the following zones are candidates for discontinuities with varying degrees of confidence: 800-950 km, weak; 630-670 km, strongest; 500-600 km, strong but interpretation in doubt; 350-415 km, fair; 280-300 km, strong, varying in depth; 100-200 km, strong, varying in depth, may be the bottom of the low-velocity zone. It is estimated that a single station cannot easily discriminate between asymmetric P'P' and P'dP' for lead times of about 30 sec from the main P'P' phase, but the LASA array reduces this uncertainty range to less than 10 sec. The problems of scatter of P'P' main-phase times, mainly due to asymmetric P'P', incorrect identification of the branch, and lack of the proper velocity structure at the velocity point, are avoided and the analysis shows that one-way travel of P waves through oceanic mantle is delayed by 0.65 and 0.95 sec relative to United States mid-continental mantle.

A new P-wave velocity core model is constructed from observed times, $dt/d\Delta$'s, and relative amplitudes of P'; the observed times of SKS, SKKS, and PKiKP; and a new mantle-velocity determination by Jordan and Anderson. The new core model is smooth except for a discontinuity at the inner-core boundary determined to be at a radius of 1215 km. Short-period amplitude data do not require the inner core Q to be significantly lower than that of the outer core. Several lines of evidence show that most, if not all, of the arrivals preceding the DF branch of P' at distances shorter than 143° are due to scattering as proposed by Haddon and not due to spherically symmetric discontinuities just above the inner core as previously believed. Calculation of the travel-time distribution of scattered phases and comparison with published data shows that the strongest scattering takes place at or near the core-mantle boundary close to the seismic station.

In Part II, the largest events in the San Fernando earthquake series, initiated by the main shock at 14 00 41.8 GMT on February 9,

1971, were chosen for analysis from the first three months of activity, 87 events in all. The initial rupture location coincides with the lower, northernmost edge of the main north-dipping thrust fault and the aftershock distribution. The best focal mechanism fit to the main shock P-wave first motions constrains the fault plane parameters to: strike, N 67° (± 6°) W; dip, 52° (± 3°) NE; rake 72° (67°-95°) left lateral. Focal mechanisms of the aftershocks clearly outline a down-step of the western edge of the main thrust fault surface along a northeast-trending flexure. Faulting on this downstep is left-lateral strike-slip and dominates the strain release of the aftershock series, which indicates that the downstep limited the main event rupture on the west. The main thrust fault surface dips at about 35° to the northeast at shallow depths and probably steepens to 50° below a depth of 8 km. This steep dip at depth is a characteristic of other thrust faults in the Transverse Ranges and indicates the presence at depth of laterally-varying vertical forces that are probably due to buckling or overriding that causes some upward redirection of a dominant north-south horizontal compression. Two sets of events exhibit normal dip-slip motion with shallow hypocenters and correlate with areas of ground subsidence deduced from gravity data. Several lines of evidence indi-cate that a horizontal compressional stress in a north or north-northwest direction was added to the stresses in the aftershock area 12 days after the main shock. After this change, events were contained in bursts along the downstep and sequencing within the bursts provides evidence for an earthquake-triggering phenomenon that propagates with speeds of 5 to 15 km/day. Seismicity before the San Fernando series and the mapped structure of the area suggest that the downstep of the main fault surface is not a localized discontinuity but is part of a zone of weakness extending from Point Dume, near Malibu, to Palmdale on the San Andreas fault. This zone is interpreted as a decoupling boundary between crustal blocks that permits them to deform separately in the prevalent crustal-shortening mode of the Transverse Ranges region.

Jordan, Thomas H., "Estimation of the radial variation of seismic velocities and density in the earth," Ph.D. Thesis, California Insti-tute of Technology, 1973.

An inversion procedure is developed to estimate the radial variations of compressional velocity, shear velocity, and density in the Earth. The radial distributions are defined as spherically sym-metric averages of the actual distributions in the laterally hetero-geneous Earth, and the nature of the averaging implied by averaging certain sets of eigenperiod and travel-time data is examined. For travel-time data, the spherical averaging yields the Terrestrial Monopole if the data sample a distribution derived from a uniform distribution of sources and receivers. Since this is difficult to obtain for absolute times, differential travel times are used to

constrain the velocities. It is shown that the bias inherent in available sets of differential travel-time data is considerably less than that in equivalent sets of absolute travel-time data, if the phase combination is suitably chosen. Observations are presented for the phase combinations PcP-P, ScS-S, P'(AB)-P'(DF), and P'(BC)-P'(DF).

The inversion algorithm developed is based on a linear approximation to the perturbation equations and is shown to provide a stable method for estimating the radial distributions of velocities and density from a finite number of inaccurate data. The linear inversion theory presented is complete; it allows one to estimate the resolving power of the data and the resolvability of specified features in the model.

Three estimates of the radial distributions are derived using an extensive set of eigenperiod and travel-time data. One model, designated model B1, fits 127 of the 177 eigenperiods of the Dziewonski-Gilbert set within their formal 95% confidence intervals. This model satisfies extensive sets of auxiliary data as well.

It is shown from resolving power calculations that little information is lost by using differential travel times in lieu of absolute times. It is demonstrated that the nature of the averaging in the estimation procedure for given sets of gross Earth data can be improved by judicious specification of the norm on the space of models.

Whitcomb, James H., "Asymmetric P'P': An Alternative to P'dP' Reflections in the Uppermost Mantle (0 to 110 KM)," Seismol. Soc. America Bull., 63, 133-143, February 1973.

Precursors to P'P' (PKPPKP), first interpreted as sub-surface reflections by Gutenberg in 1960 and studied in several later papers by other authors, precede the P'P' phase by up to 200 sec. This phase, designated P'dP' where d is the depth of reflection, has unique potential for giving new details of upper-mantle structure. However, as with any newly discovered seismic phase, the uniqueness of its interpretation must be well established. Asymmetric P'P' phases reflecting from surface or near-surface dipping interfaces pose a challenge to this uniqueness because of their maximum-time nature. Simplified estimates of the amplitudes of asymmetric P'P' rays are made, including consideration of the relative amplitudes of core phases and the finiteness of the reflecting surfaces of dipping interfaces. These estimates lead to the conclusion that the reading of asymmetric P'P' at a single station is likely only in the 0- to 30-sec range before the main symmetric P'P' phase. However, if array beam-forming is used,

this range is reduced to 0 to 10 sec. The data indicate that both P'dP' and asymmetric P'P' are present at up to 30 sec lead time and array beam-forming is needed to differentiate between the two. A further effect of the maximum-time nature of P'P' is that, in practice, the geographic location of the reflection point can be determined to within only a few degrees.

Abstracts of Papers Submitted for Publication:

Hron, F. and E. R. Kanasewich, "Synthetic Seismograms for Deep Seismic Sounding Studies Using Asymptotic Ray Theory," submitted to Seismol. Soc. America Bull.

In asymptotic ray theory the solution for particle motion is assumed to be an infinite power series of inverse frequency and a vector amplitude, $A_n(x,y,z)$, independent of frequency. A point source with any desired impulse response and radiation pattern is easily incorporated. A synthetic seismogram computer program has been written for a plane layered homogeneous elastic medium using the first or second terms of the expansion where necessary. Multiply converted refracted and reflected phases and also head waves at distances away from the critical angle are included. In addition, the phases are all identified and their amplitude-distance function plotted if desired. The synthetic seismograms are calculated for a model in southern Alberta and another in northwestern Ontario as obtained by deep seismic sounding programs. It is found that reflected phases dominate the seismograms and they are at least as important as head waves in the interpretation of experimental results.

Kurita, Tuneto, "Upper Mantle Structure in the Central United States from P and S Wave Spectra," submitted to Seismol. Soc. America Bull.

In order to study regional variations in the upper mantle structure in the central United States, the second step of a two step procedure formulated in Kurita (1972a) has been taken and experimentally shown to be a very powerful method for elucidating the fine configuration of the low-velocity zone. The strong advantage of this method as compared with the other methods is a mutual independency of the extent of the velocity decrease and the depth to the bottom of the low-velocity zone. The upper mantle structure down to about 220 km in this region has been inferred from complex transfer ratios of long period P and S waves from deep-focus earthquakes recorded at FLO, OXF, and SHA on the basis of the crustal models obtained in Kurita (1972b). From the Interior Plain to the Gulf of Mexico the low-velocity zone

shifts to a shallower depth while increasing its thickness and decreasing its velocity. This zone is about 50 km thick layer ranging in depth from about 150 to 200 km under the Interior Plain, about 75 km thick layer from about 120 to 195 km under the Gulf Coastal Plain, and about 80 km thick layer from about 95 to 175 km under the continental shelf of the Gulf of Mexico, all nearly along 89°N longitude. The decrease in S wave velocity at the top of this zone is about 0.30, 0.45, and 0.70 km/sec under each of the areas above, although the last value may be somewhat an overestimate. Both boundaries of this zone are sharp, the transition occurring over at most about 10 km. In this region the existence of the high-velocity lid zone is possible.

Kurita, Tuneto, "Regional Variations in the Structure of the Crust in the Central United States from P Wave Spectra," submitted to Royal Astron. Soc. Geophys. Jour.

Regional variations in the crustal structure in the central United States has been inferred from the complex transfer ratio of long period P waves recorded at four WWSSN stations, SHA, OXF, FLO, and MDS. The crustal structure in this region is approximated by a stack of horizontal parallel layers except possibly the area around FLO where the structure is rather complicated. Deep discontinuities in the crust may possibly be replaced by transitional layers up to 10 km thick. The depth to the Moho is about 33 km near the Gulf of Mexico, deepens to about 41 km near the intersection of the Gulf Coastal Plain and the Interior Plain, reaches about 47 km or more in the midst of the Interior Plain, and rises to about 41 km toward the intersection of the Interior Plain and the Superior Upland. The thickness of the silicic upper crust, having a velocity of about 6.0 to 6.5 km/sec in each of the regions above is about 15, 30, 35, and 30 km respectively, whereas the thickness of the mafic lower crust is about 10 km throughout the entire region. The velocity of the lower crust is about 6.9 to 7.0 km/sec except probably for the area around FLO where about 7.4 km/sec velocity is more likely. The existence of a near-surface layer with a velocity of about 4.7 to 5.4 km/sec and having a thickness of 1 to 3 km is a prevailing feature. A sedimentary layer with a velocity of about 3.0 km/sec and having a thickness of about 3 km on the Gulf of Mexico is confined to the Gulf Coastal Plain and tapering out to the north. When two or more crustal models are appropriate for a limited region, the crustal effect may be eliminated from observed spectra with sufficient accuracy by assuming either of the models.

Minster, J. B., "Transformation of Multipolar Expansions under Rota-
tion of the Coordinate System," submitted to Royal Astron. Soc.
Geophys. Jour.

A simple and convenient formula describing the transformation
of a multipolar expansion under an arbitrary proper rotation of the
reference frame is derived. When combined with the known correspond-
ing formulae for a translation, these results show how multipolar
expansions transform under any proper displacement of the reference
frame. Particular emphasis is placed on the seismic source problem;
however, these results find applications in many other physical prob-
lems.

Niazi, Mansour, "SH Travel-Times and Lateral Heterogeneities in the
Lower Mantle," submitted to Seismol. Soc. Am. Bull.

The horizontal long period seismograms of two shallow earth-
quakes in Turkey and Iran recorded in selected azimuths are combined
for travel time studies of SH-wave beyond angular distance of 40 de-
grees. The observed travel times along two profiles which sample deep
mantle in the vicinity of Iceland and the North Pole show monotoni-
cally increasing differences beyond 65 degrees, indicating lateral
heterogeneity in the lower mantle. The travel time difference becomes
as large as 7 sec at 95 degrees, implying a variation as much as
0.06 km/sec, or about 1%, in the shear wave velocity near 2500 km
depth. Inversion of observations, adjusted to surface foci, results
in an average lower mantle structure with lower shear velocities than
those given by Jeffreys. The difference exceeds 0.1 km/sec at the
core boundary.

The arrival time and signature of S waves recorded in Greenland
show anomalous features which may be related to deep seated anomalous
zones associated with Mid-Atlantic Ridge system.

Kanamori, Hiroo, "Long-Period Ground Motion in the Epicentral Area,"
submitted to Tectonophysics.

In view of the potential importance of long-period ground motion
in the design of large structures, near-field ground displacement is
computed by the elastic dislocation theory for several earthquake fault
models. The validity of such computations is confirmed by comparing
the computed seismogram with the observed long-period seismogram of the
1923 Kanto earthquake. The ground motions are computed for three
hypothetical earthquakes, a hypothetical Kanto earthquake, Tokai earth-
quake and Nemuro-Oki earthquake. The location and nature of the

faulting of these earthquakes are predicted by plate tectonics and precise earthquake mechanism studies. Major conclusions are: Tokyo may suffer, in the hypothetical Kanto earthquake, ground motions about half as large as those experienced in the 1923 Kanto earthquake; Hamamatsu, a large city on the Tokai coast, may experience in the hypothetical Tokai earthquake ground motions which are as large as, or even larger than, those experienced in the epicentral area of the 1923 Kanto earthquake; the hypothetical Nemuro-Oki earthquake may cause ground motions as large as those experienced in the 1968 Tokachi-Oki earthquake on the coastal cities in Hokkaido.

Helmberger, Donald V., "On the Structure of the Low Velocity Zone," submitted to Geophys. Jour.

Body wave observations from large nuclear explosions at the Nevada Test Site have been used to model the P-velocity and Q structure along the top of the mantle. The amplitudes of short period waves in the range 1 to 4 degrees and 12 to 35 degrees indicate substantial absorption in the low velocity zone with Q_{α} of the order of 50. With the source treated as a known quantity we used the amplitude ratio of short to long period motion as a criterion in modelling structure. The Cagniard-deHoop technique is used to compute synthetic seismograms for proposed models. The model obtained has a high velocity lid above a thin pronounced low velocity layer with a small positive gradient existing to depths of 220 km. The shadow zone boundary occurs near 12 degrees.

Helmberger, Donald V., "Numerical Seismograms of Long Period Body Waves from 17 to 40°," submitted to Seism. Soc. Am. Bull.

Long period wave propagation in the upper mantle is investigated by constructing synthetic seismograms for proposed models. A model consisting of spherical layers is assumed. Generalized ray theory and the Cagniard-deHoop method is used to obtain the transient response. Preliminary calculations on producing the phases P and PP by ray summation out to periods of 50 sec is demonstrated, and synthetic seismograms for the long period WWSS and LRSM instruments are constructed.

Models containing prominent transition zones as well as smooth models predict a maximum in the P amplitude near 20°. The LRSM synthetics are quite similar for the various models since the instrument is relatively narrow band, peaked at 20 sec. The upper mantle appears smooth at wavelengths greater than 200 km. On the other hand, the WWSS synthetics are very exciting for models containing structure. The triplications are apparent and the various pulses contain different periods.

The amplitude of the P phase at 30° is down to about 25 percent of its 20° maximum. The amplitude of the PP phase at 35° is comparable to P . Near 37° the PP phase grows rapidly reaching about twice the P phase amplitude near 40°. Models containing sharp transition zones produce high frequency interferences at neighboring ranges. A profile of observations is presented for comparison.

Mitchell, Brian J., and Donald V. Helmberger, "Shear Velocities at the Base of the Mantle from Observations of S and ScS," submitted to Jour. Geophys. Research.

The observed amplitude ratios of transversely polarized shear waves, ScSH/SH, include a minimum at a distance of about 68°. Synthetic seismograms computed for a Jeffreys-Bullen model and for models with negative linear velocity gradients at the base of the mantle fail to explain this feature. Various positive linear velocity gradients above the core-mantle boundary explain the amplitude ratio minimum as well as an apparent difference in arrival times of the transversely and radially polarized core reactions, ScS. Good agreement between the observed and computed amplitude ratios cannot be achieved without assigning low Q values to the lower mantle or a small shear velocity value to the outer core.

At epicentral distances greater than 70°, a substantial portion of the energy recorded as a horizontally polarized ScS wave bottoms at various depths in the high velocity region rather than at the core-mantle interface. These precursory arrivals are in phase with the core reflections on the transverse component and out of phase with them on the radial component. This causes an apparent time differential by which the transversely polarized ScS wave seems to arrive slightly earlier than the radially polarized ScS wave.

High velocity regions between 40 and 70 km thick, containing increases from 0.3 to 0.5 km/sec above that of a Jeffreys velocity model yield the best explanation to the combined amplitude and differential time data.

Jordan, Thomas H., and Don L. Anderson, "Earth Structure from Free Oscillations and Travel Times," submitted to Geophys. Jour.

An extensive set of reliable gross Earth data has been inverted to obtain a new estimate of the radial variations of seismic velocities and density in the Earth. The basic data set includes the observed mass and moment of inertia, the average periods of free oscillation (taken mainly from the Dziewonski-Gilbert study), and five new sets of differential travel-time data. The differential travel-time data

consists of the times of PcP-P and ScS-S, which contain information about mantle structure, and the times of $P'_{AB}-P'_{DF}$ and $P'_{BC}-P'_{DF}$, which are sensitive to core structure. A simple but realistic starting model was constructed using a number of physical assumptions, such as requiring the Adams-Williamson relation to hold in the lower mantle and core. The data were inverted using an iterative linear estimation algorithm. By using baseline-insensitive differential travel times and averaged eigenperiods, a considerable improvement in both the quality of the fit and the resolving power of the data set has been realized. The spheroidal and toroidal data are fit on the average to 0.04 and 0.08 percent, respectively. The final model, designated model B1, also agrees with Rayleigh and Love wave phase and group velocity data.

The ray-theoretical travel times of P waves computes from model B1 are about 0.8 seconds later than the 1968 Seismological Tables with residuals decreasing with distance, in agreement with Cleary and Hales (1968) and other recent studies. The computed PcP, PKP, and PKiKP times are generally within 0.5 sec of the times obtained in recent studies. The travel times of S computed from B1 are 5 to 10 sec later than the Jeffreys-Bullen Tables in the distance range 30° to 95°, with residuals increasing with distance. These S times are in general agreement with the more recent data of Kogan (1960), Ibrahim and Nuttli (1967), Lehmann (1964), Cleary (1969), and Bolt et al. (1970).

Model B1 is characterized by an upper mantle with a high, 4.8 km/sec, S_n velocity and a normal, 3.33 gm/cm^3, density. A low-velocity zone for S is required by the data, but a possible low-velocity zone for compressional waves cannot be resolved by the basic data set. The upper mantle transition zone contains two first-order discontinuities at depths of 420 km and 671 km. Between these discontinuities the shear velocity decreases with depth. The radius of the core, fixed by PcP-P times and previous mode inversions, is 3485 km, and the radius of the inner-core-outer-core boundary is 1215 km. There are no other first-order discontinuities in the core model. The shear velocity in the inner core is about 3.5 km/sec.

III. Previous Technical Reports

Previous Technical Reports

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Kurita, T., Upper mantle structure in the central United States from P and
     S wave spectra: submitted to Seismol. Soc. America Bull.

Kurita, T., Regional variations in the structure of the crust in the central
     United States from P wave spectra: submitted to Royal Astron. Soc.
     Geophys. Jour.

Minster, J. B., Transformation of multipolar expansions under rotation of
     the coordinate system: submitted to Royal Astron. Soc. Geophys. Jour.

Niazi, M., SH travel-times and lateral heterogeneities in the lower mantle:
     submitted to Seismol. Soc. America Bull.

Kanamori, H., Long-period ground motion in the epicentral area of major
     earthquakes: submitted to Tectonophysics.

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     Royal Astron. Soc. Geophys. Jour.

Helmberger, D. V., Numerical seismograms of long period body waves: submitted
     to Seismol. Soc. America Bull.

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